why did it fall into disrepute in the middle of the nineteenth century?

This mystery was brilliantly resolved by Alice Henderson Smith (1918) who traced the events from the beginning of the nineteenth century. As we know, by 1810, in the Royal Navy, all records of scurvy cease. It turns out that 'lime juice' was a misnomer – it referred actually to the juice of lemons. They came from Spain, but in 1796, as a result of the war, they then came from Lisbon, but here the supply was uncertain, and the source was once again switched, this time to Malta and Sicily. The supply was now good enough to allow it on general ration instead of only for the sick and on foreign voyages.

By the middle of the nineteenth century, there were complaints of the quality of the Malta lemon; the Admiralty wanted to take no chances, especially with the Arctic ships, so they made new arrangements. The West Indies were now growing limes, produced by English firms there, who could be relied on for high standards of fruit production. By now, it was thought that the antiscorbutic virtue lay in the acidity, and reports were coming that West Indian limes were of high acidity. The Admiralty transferred its contracts, and by 1870 very little real lemon juice was supplied.

In 1847–59, McClure's ships were immune from scurvy because they had real lemon juice, although called 'lime juice'. Nare's expedition in 1875 suffered from scurvy because they had the juice of West Indian limes. It was, in retrospect, an excellently controlled experiment, but it merely added to the disrepute of real lemon juice. It was shown years later that the West Indian lime juice contained barely one-quarter of the ascorbic acid of mediterranean lemon juice. Thus, for all Shackleton's precautions, had he relied entirely on the capsules of juice, he would have had trouble with scurvy (Medical Research Council 1932).

(2) Whatever happened to the acid intoxication theory of scurvy? Almroth Wright clung doggedly to his theory, although it turned out to be a symptom of the disease rather than the basic cause.

It was only in 1937, when Lewis Holt showed him that if scorbutic guinea-pigs were given pure crystalline ascorbic acid they were cured of experimental scurvy and that this substance could prevent the condition, that Wright capitulated.

There is nothing that does not confirm Captain Scott as a wise and meticulous leader, and a man of his time – no better, no worse. And those of us who have had medical responsibilities on polar expeditions are extremely humble and grateful that in our day we do not have the agonizing lack of knowledge in these matters which applied half a century ago.

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The Logistics of the Polar Journeys of Scott, Shackleton and Amundsen

The problems of travel in Antarctica have been finally solved with the introduction of motor vehicles, tractors and support aircraft. Radio communication and modern methods of navigation have played a part by making it possible to maintain contact with small parties on the polar plateau and surrounding mountains, and to visit them at will.

But of more interest physiologically and medically are the journeys of Scott, Shackleton and Amundsen between the years 1901 and 1912, and my purpose is to consider these in the light of physiological information collected by a later generation.

I shall begin by summarizing the accounts of the respective expedition leaders. In comparing them it is well to bear in mind that neither Scott nor Shackleton had any experience of polar travel or living in snow when they first went to Antarctica with the *Discovery* expedition in 1901–03. Amundsen, on the other hand, was an extremely experienced explorer. He and his companions had been brought up to ski and travel on snow and were accustomed to a cold environment.

The Discovery *Expedition (1901–03)*

This expedition completed a formidable programme of exploration during which Scott and his companions learnt the art of polar travel.

His most instructive journey was the 'Farthest South' journey between November 2, 1902, and February 3, 1903, during which with Shackleton and Wilson he covered 833 geographical miles (959 statute miles)[1] in 93 days, reaching a latitude of 82° 17′ S.

Scott, Shackleton and Wilson started from Hut Point on November 2 with three sledges and 13 dogs. They were preceded by a support party of 12 men hauling sledges. The support party left a depot (A) in latitude 79° or thereabouts, and half of them returned from there. The rest turned back on November 15. The intention was by this means to extend the range of Scott's party from nine weeks to 13 weeks. At this point in his narrative there is a discrepancy, for he states that there were 19 dogs, and he gives a plan showing five sledges carrying 1,852 lb (842 kg) gross. He goes on to say that at first the dogs travelled so fast that the men could not keep up with them, and they increased their loads to 2,100 lb (953 kg) so as to slow them down. The party had skis but were apparently too inexperienced to make good use of them.

The dogs were fed on Norwegian dried fish, which did not agree with them, and they soon began to deteriorate. By the beginning of December they were exhausted, and on December 8 the first dog died. From then on the dogs were sacrificed one by one, and by the end the whole team had been lost. With failure of the dog team the men took over, and this necessitated relaying the sledges. They continued thus for 31 days, covering only 3–5 miles a day.

In spite of these setbacks the party pushed on southward. They laid a depot (B) in latitude 81° 30′, 330 miles (378 st. miles) from Hut Point. On December 30 they reached latitude 82° 17′, which was their furthest point south. By this time they were pulling 170 lb (77 kg) loads at 1 mph. Food and fuel were short. The fuel ration of one gallon (4·5 l.) for 13 days was found to be insufficient. Scott saw that his party was becoming weaker from lack of food, and realized his mistake in attempting to save weight by restricting their diet. There was also the problem of scurvy which had shown itself in Shackleton and, to a lesser extent, in Scott himself. The party eventually got back to Hut Point on February 3, having covered 833 miles in 93 days.

Shackleton's Journey to the Pole (1908–09)

Shackleton, Wild, Marshall and Adams set out from Hut Point on November 3, 1908, with a support party and four Siberian ponies pulling sledges loaded to a total weight of 600–660 lb (272–300 kg) each, including 153 lb (69 kg) of pony food. The rations had been calculated to last 93 days, but Shackleton hoped to spin them out to 120 days. On November 14 they reached Depot A, laid the previous spring. On November 18 they passed latitude 82° 18′, Scott's furthest south, having taken 25 days compared with Scott's 51 days. They had already laid Depot B and shot one pony. Another was shot at Depot C, where they left oil and provisions for a week to take them back to Depot B. They now had two sledges each pulled by one pony and two men, and they repacked the sledges to take 1,200 lb (544 kg) – 630 lb per sledge (286 kg) – which Shackleton hoped would keep them going for nine weeks. On December 1 a third pony was shot. Once they got on the glacier they realized the remaining pony must be considered as a source of food rather than a source of traction. A further depot, D, was laid on December 7 at the altitude of 1,700 ft (518 m) on the glacier. They were now pulling loads of 250 lb (113 kg) each and having to relay on difficult sections. On December 17 they laid Depot E at a height of 6,000 ft (1,829 m). They were carrying only six weeks' rations but were saving two biscuits a day each, besides some pemmican and sugar. They had for some time been suffering severely from hunger. A final depot, F, was laid in latitude 88°. On January 9 they reached their furthest point – latitude 88° 23′ – 77 miles (88 st. miles) from the South Pole.

On the return journey their food supplies were even more restricted. Between Depot B and Depot A on the return journey their rations consisted of 1½ cups of meat and gravy, 3 spoonfuls of pemmican, 6 biscuits and ½ spoonful of sugar – about 1,750 calories compared with a requirement of at least 5,000 calories. Adams became ill with diarrhœa and was left at Depot A with Marshall to look after him. Shackleton and Wild then force-marched the rest of the way, covering 78 miles (89 st. miles) in four days in spite of their weakened condition (Shackleton had lost 24 lb (10·9 kg) in weight). They arrived at Hut Point on February 28.

Amundsen (1911–12)

Amundsen's base, Framheim, was at the Bay of Whales, 300 miles to the east of Hut Point in latitude 78° 50′. All his travelling was done on skis, the sledges being pulled by teams of dogs, of which he had 110 at his disposal. He started establishing depots for the journey south during the previous spring. Depots were laid at 80°, 81° and 82°S and included three tons of provisions and 22 cwt (1,118 kg) of seal meat. The loaded sledges weighed 660 lb (299 kg) and were pulled by teams of six dogs. In good conditions they were capable of up to 52 miles (60 st. miles) in a single day.

Amundsen set out on the journey south on October 20, 1911, with four companions and four sledges each pulled by 13 dogs making 52 in all. They travelled light to the first depot, covering 86 miles (99 st. miles) in four marches, and then picked up their full loads. At the second depot (latitude 81°) they allowed the dogs to gorge themselves on seal meat. At Depot 3 (latitude 82°) the dogs for the last time were allowed as much pemmican as they could eat, and the party rested three days. They started again on November 8, leaving depots at every parallel. On November 17, in latitude 85°, they established a main depot on the coast line leaving supplies for 30 days and taking with them supplies for 60 days. Several dogs had by this

[1] 1 geographical mile = 1 minute of latitude = 1·151 statute miles

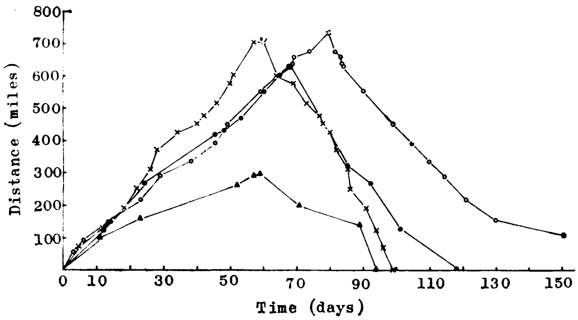

Fig 1 *Plot of distance travelled against time taken during the polar journeys of Scott 1902–03* (▲——▲), *Shackleton 1908–09* (●——●), *Amundsen 1911–12* (x——x) *and Scott 1911–12* (O——O). *Distance shown in geographical miles*

time been shot because they could not keep up, or had deserted. Amundsen apparently did not tether his dogs as is customary in British exploration. Up to this point the men had been pulled on skis behind the sledges and had a comparatively easy time of it. During the 100 mile (160 km) ascent of the Axel Heiberg Glacier they relayed their sledges on the steeper slopes, hitching 20 dogs to each of two sledges and returning for the remaining two sledges. In this way they were able to ascend as much as 2,000 ft (610 m) in a single day.

On reaching the plateau at 7,600 ft (2,316 m) they rested four days and slaughtered 24 dogs. Amundsen says his dogs would not eat their dead companions unless the skin had been removed. This contrasts with the behaviour of Scott's dogs when they were being fed on unsuitable rations. Scott says in his account that whenever they shot a dog the rest fell upon it and devoured it immediately.

From Butcher's Camp they proceeded with three sledges and 18 dogs, laying depots at each degree of latitude and marking the route with flags. Dogs were sacrificed as the loads became lighter, and by the time they reached the Pole they had 12 dogs and two sledges left. The maximum altitude of 11,025 ft (3,360 m) was reached in latitude 87° 51′, after which they descended to about 9,500 ft (2,896 m), which is the altitude of the South Pole. They reached the South Pole on December 14 and spent three days there fixing their position. On December 16 they took hourly observations with the sextant for 24 hours. According to the sledge meters they had covered 755 miles (869 st. miles), averaging 15 miles a day. The lowest temperature encountered had been −23°F (−30·5°C) and the highest +23°F (−5°C).

The return journey from the Pole was accomplished in 39 days. They started back on December 17 and reached Framheim on January 25, 1912, with two sledges and 11 dogs. The five men and their dogs were described as being strong and in good health. They had had plenty to eat throughout the journey: the rations consisted of biscuit (made of oatmeal, sugar and dried milk), pemmican, cocoa, chocolate, seal meat and dog meat. Assuming the biscuit ration was 16 oz/day, we can put the calorie intake at 4,600–5,000 kcal/day.

Amundsen says the total distance of 1,615 miles (1,859 st. miles) was covered in 99 days at the average speed of 17 st. miles (27 km) a day. The remarkable features of this journey are the speed of travel and the ample reserves of food, so that both men and dogs maintained their strength.

Scott's Journey to the Pole (1911–12)

Scott set out for the Pole a fortnight later than Amundsen. His logistic policy differed from Amundsen's in that he laid only one depot in advance (One Ton Depot, latitude 79° 40′) and took with him a large support party to lay his depots as Shackleton had done in 1908.

Sixteen men with two tractors, a dog team and five ponies left Cape Evans on November 1 and started from Hut point on November 2. The motor vehicles failed almost at once, but the ponies and dogs did good service as far as the Beardmore Glacier which they reached in 37 days. By this time the ponies were weakening owing to poor surfaces, and their food supply was nearly exhausted. The first pony was shot at Camp 24 and the remaining four at Camp 31 on December 9. Two days later Meares and the dog team were sent back. This left three teams of four men each to haul three sledges up the Beardmore Glacier. An extra 200 lb (91 kg) weight had been added to each sledge when the dog team left. Each man now had to haul about 250 lb (113 kg) in weight. This proved very exhausting, especially in soft snow and on gradients. They were soon reduced to relaying and covered only 3–5 st. miles a day. On December 21, near the top of the Beardmore Glacier, Atkinson and his team were sent back, and on January 1 three of the four men in the second team were ordered back, leaving Scott and his four companions with a single sledge to push on to the Pole. During this phase Scott used a special ration – the summit ration – which provided about 5,000 kcal. They made their way across the plateau, leaving dumps at intervals, and arrived at the Pole on January 18, leaving again the same day.

On the return journey they made good progress as far as the Beardmore Glacier, covering 180 miles (207 st. miles) in 17 days, but progress became increasingly slow thereafter owing to physical deterioration associated with vitamin deficiencies. Owing to the slow progress they had to spin out their rations and were caught by deteriorating weather which is usual in the area after the beginning of March. In addition they took a day off near the bottom of the Beardmore Glacier to collect geological specimens. Finally, between latitude 82° and latitude 80°, they were reduced to six miles a day, taking 17 days to cover 120 miles (138 st. miles). Temperatures by this time had fallen as low as −43°F (−41°C) and they were held up by blizzards. At their last camp, 9·5 miles (11 st. miles) short of One Ton Depot, they ran out of fuel.

Mobility

The first aspect worth considering is the mobility achieved by the various parties as a result of their different methods of travel.

Fig 1 is a distance/time plot of the four journeys. The chart shows the striking increase in mobility and endurance achieved by Shackleton in 1908–09 using ponies compared with Scott six years earlier using dog teams. Shackleton's journey was almost exactly reproduced by Scott in 1911–12, but Shackleton had fewer supplies and was forced to turn back, whereas Scott, who had two support parties on the Beardmore Glacier, was able to push on to the Pole, although in doing so he became dangerously late.

It is surprising to find that although Amundsen could travel faster with his dog teams than Scott and Shackleton with their ponies, the three parties covered the first 300 miles (345 st. miles) across the ice-shelf in much the same time. Amundsen and his companions, however, exerted themselves less since they travelled on skis being pulled by the dog teams. The superiority of the dog teams begins to show itself on the 8,000 ft (2,440 m) ascent to the polar plateau and in the dash to the Pole. By the time Amundsen reached the Pole he had covered nearly 200 miles (230 st. miles) more than Scott had in the same time, and had gained 23 days in addition to his earlier start.

Supplies

Amundsen's reserve of provisions and fuel was built up mainly during the previous season when he laid three tons of stores, including 22 cwt (1,118 kg) of seal meat, in depots extending as far south as latitude 82°. It was largely the hauling power and speed of his 110 dogs that made this possible.

In addition to his greater transport capacity, Amundsen made available some 2,000 lb (910 kg) of fresh meat by slaughtering his dogs. He expressed the opinion that it was less cruel to feed and work dogs correctly and then shoot them, than to starve and overwork them to the point of collapse like the Englishmen. In point of fact, resistance on the part of Scott and Shackleton to the idea of shooting their dogs for food was hardly logical, in view of the fact that both alike sacrificed their ponies before ascending the Beardmore Glacier.

After the 'Farthest South' experience in 1902–03, Scott and Shackleton must have realized that there would be little hope of transporting enough supplies for a party to reach the South Pole without some form of transport other than manhauling. Having failed to master the art of dog sledging they tried other methods, including mechanical transport, Siberian ponies and even sail. Of these, the ponies were the most successful.

Energy Cost of Sledging

Taylor (1957) measured the work output of sledge dogs with an electric strain-gauge. He found that the maximum pull that could be expected from a team of nine dogs was 137 kg weight. Maximum sustained output occurred when the dogs were trotting at 5 mph (8 km/h) with a drag of 55 kg weight, or walking at 3·2 mph with a drag of 95 kg. The maximum useful output represented 1,100 kcal during one hour, or 1·78 hp (1,268 W). Hence the sustained output of the average dog (39 kg) was about 0·2 hp (149 W).

On this basis, Amundsen, with his 52 dogs, had 9 hp (6,714 W) at his command all the way to the polar plateau. Shackleton and Scott, on the other hand, can hardly have had more than 2–3 hp (1,490–2,238 W) from their ponies and then only as far as the Beardmore Glacier.

A 75 kg man accustomed to prolonged and severe exercise may be expected to maintain an O_2 intake of 2·0 l./min for long periods. Brotherhood & Pugh (unpublished results) found that a man pulling a load on the treadmill, by means of a belt attached to weights, was able to pull 11 kg at 2 mph (3·29 km/h) with an O_2 intake of 2·0 l./min and an efficiency of 24% (Fig 2). This is equivalent to a power output of 0·13 hp (97 W). On a snow surface the useful power output may be somewhat less than this, and the value of 0·08 hp (60 W) for soldiers pulling pulkas (Daniels & Vaughan 1956) seems acceptable. It would seem that the dog is about twice as efficient as man at hauling sledges, for their daily energy requirements are comparable.

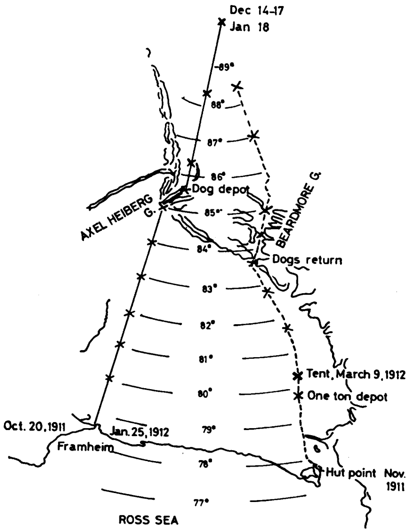

Fig 2 *Diagram showing routes taken by Amundsen (———) and Scott (- - - - -) to the South Pole. Crosses indicate positions of major dumps*

Table 1
Energy value of sledging rations

	Weight (oz)	*Energy value (kcal)*
Scott 1911–12: summit ration	34·4	5,100
Mawson 1962	34·25	5,100
Amundsen 1911–12	—	5,000
British Graham Land Expedition 1934–37	25·5	4,000
FIDS 1948–50	25·5	4,100
FIDS 1958	27·45	3,900
MRC experimental 1959	36·25	5,400

Average composition of above rations

	Proteins	*Fats*	*Carbohydrates*
Percentage	22	34	44
Grams	275	189	550

It is obvious that the efficiency of moving on snow and therefore the power available for hauling sledges depends on the condition of the snow surface. This is shown by the fact that men may haul a sledge 20 miles (32 km) a day in good conditions but travel only 3–5 miles (5–8 km) in soft snow, and sometimes hardly at all unless they have skis or snow shoes. The same is true of dogs hauling sledges, although experience shows they are less affected by bad conditions than men.

Food Requirements of Men and Sledge Dogs
Scott and Shackleton allowed about 1 lb (0·45 kg) of food per dog per day for sledging, and 2 lb (0·9 kg) per man per day.

Orr (1962) has shown that 80–90 lb (36–41 kg) sledge dogs need 5,000–6,000 kcal of food a day to prevent weight loss during sledge trips, and Taylor *et al.* (1959) and Wyatt (1963) have shown that sledge dogs need 3,000 kcal of food even when they are not working. These values compare closely with the accepted values for men (Table 1) during sledge trips and at base.

It has been further shown (Orr 1964, Taylor 1957) that when dogs are fed on pemmican or nutrican they may lose 25–30% of the energy value of the food in their stools. The ideal food for sledge dogs is seal meat with the blubber attached. This has an energy value of approximately 2,000 kcal/lb, so that 5,000 kcal can be obtained from 2·5 lb (1·1 kg) of it. No polar expedition has succeeded in reducing the weight of its sledging ration for men below 2 lb (0·9 kg) for 5,000 kcal and 2·5 lb (1·1 kg) gross is a realistic allowance. Thus men and dogs need the same allowance of food for sledge journeys in Antarctica.

Various authors (*see* Orr 1964) have shown that when sledge dogs are given insufficient food they become difficult to handle and their work output suffers. Likewise it is well established that the work output of men in the long term is a linear function of their food intake.

Dill *et al.* (1932) demonstrated that given adequate food and fluid and a cool environment the dog is practically inexhaustible. In one case a dog ran for 17 hours with five-minute rest periods each half hour. In the 17 hours it ran 82 miles (132 km) and climbed 14 miles (23 km). Its work capacity was increased by more than three times by supplying fuel. From more recent data we can calculate that the oxygen intake necessary for a man to work at this rate would be 54 ml kg^{-1} min^{-1}, which is more than the maximum oxygen intake of most well-trained men who are not track athletes.

Vitamin Deficiencies
Although this aspect does not strictly belong to logistics, the question arises whether vitamin deficiencies may have been one of the factors responsible for Scott's failure with sledge dogs. Taylor *et al.* (1959) claim that the thiamine requirement of a 90 lb (41 kg) sledge dog is about 0·7 mg per day, whereas the usual sledging ration consisting of 1 lb of pemmican contains only 0·4 mg of thiamine. They found evidence of reduced urinary excretion of both thiamine and riboflavin in dogs kept in metabolism cages on a pemmican diet, and cited evidence showing that in young dogs receiving diets deficient in riboflavin or pantothenic acid forced exercise may lead to collapse in hypoglycæmic coma. They suggest that this may have been a cause of collapse reported in working sledge dogs after long periods on pemmican. No data are given, however, on a dried fish diet such as Scott used. With regard to vitamin C deficiency, it appears that dogs can synthesize enough vitamin C to prevent serious deficiency occurring, even on long sledge journeys.

Planning
In planning his journeys Scott tells us he divided his loads into (*a*) nonconsumable items, and (*b*) consumable items. The nonconsumable items included the sledges, sleeping bags, tents, stove, tools, instruments, &c. The consumable items consisted of rations at 2–2·5 lb (0·9–1·1 kg) per man per day, fuel, and food for dogs and horses.

The nonconsumable weight was fixed and independent of the duration of the trip. The consumable stores, on the other hand, varied with time and were the factor limiting the duration of the trip.

It is instructive to go further than this and consider the consumable stores in terms of (*a*) requirements dependent on the duration of the journey and (*b*) requirements dependent on the distance covered. The former may be referred to as fixed stores and the latter as variable stores.

Under the heading of fixed stores come fuel and food for resting metabolism. The fuel requirement for sledging is about 0·75 pint

(0·45 kg) per man per day. If we take a 1 kg daily food ration having an energy value of 5,000 kcal, approximately 2,000 kcal will be needed for resting metabolism, leaving 3,000 kcal for locomotion. The fixed weight of rations will therefore be $1 \times \frac{2,000}{5,000} = 0{\cdot}4$ kg, making a total of 0·85 kg per man per day for fixed stores. The variable stores, on the other hand, will be $1 \times \frac{3,000}{5,000} = 0{\cdot}6$ kg per man per day, providing 3,000 kcal.

The energy cost per mile of sledging varies of course with snow conditions, gradients and other factors, but an overall average figure of 10 miles for 3,000 kcal or 300 kcal/mile is reasonable. The requirement for 1,000 miles will be 300,000 kcal/man and will be the same whether a party takes 100 days or 75 days to cover the distance, and the corresponding weight will be 60 kg per man for 1,000 miles.

Thus to cover 1,000 miles in 100 days requires 85 kg of fixed stores plus 60 kg of variable stores, which equals 145 kg per man. To cover the same distance in 75 days costs 63·5 kg plus 60 kg= 123·5 kg per man. For a four-man party the extra weight required for the slower journey amounts to 86 kg (190 lb) or one extra sledge load for one man or two dogs.

Parties using animal transport have, of course, a mobile food store available, as well as more pulling power.

The importance of weight economy, which has dominated the thinking of expedition leaders not only in polar but also in mountain exploration, has led to restriction of rations and fuel of such a degree that parties have been unable to obtain sufficient food or fluid to maintain their strength, and their physical performance has suffered accordingly. Scott realized this mistake on his 'Farthest South' expedition and tried to ensure an adequate ration for his polar journey. Unfortunately, towards the end, food supplies became short and fuel ran out owing to delays and leakage of fuel from cans stored in the depots. What British explorers did not realize, and have not realized until recently, is that a dog, if it is to do the same amount of work as a man, will require the same amount of food. The extra mobility afforded by dogs by virtue of their higher speed was not appreciated as it was by the Norwegians. Not only were the Norwegians accustomed to ski, which enabled them to keep up with their dogs and exploit their greater speed, but they also understood how to feed them and not overwork them.

One final point worth mentioning is the variation of food requirements according to body size. It seems reasonable to suppose that Scott's party, returning from the Pole, shared their rations equally, and if this were so Seaman Evans, who was a large man, would have had less food per kilogram of body weight than Bowers, who was a small man. For example, the difference would be as much as 45% if Evans weighed 80 kg and Bowers 55 kg. It has been suggested that the severe deterioration in Evans and comparatively good condition of Bowers on the return journey from the Pole might be explained on this basis.

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My contribution to this symposium is a double story: the first part is an account of the demise of the acid intoxication theory of scurvy and the second part is how a great man coped with the demise of a favourite theory.

In 1934 I obtained a degree in physiology at University College London where my professor of physiology was Professor Lovatt Evans, and the professor of biochemistry was J C Drummond. Immediately on leaving college, I joined Professor Alexander Fleming at the Inoculation Department at St Mary's Hospital, W2, as a bacteriological assistant. The director of the department was Sir Almroth Wright (professor of experimental pathology). Before long Wright (the Old Man) lectured me on his acid intoxication theory of scurvy, where, according to Wright, the particular merit of vegetables was their alkaline residue after normal metabolic action. Naturally I referred to the new theory of scurvy being a deficiency disease, where the all-important substance was an *acid*, called ascorbic or hexuronic acid. This account of the cause of scurvy called forth a storm of ridicule, whereupon